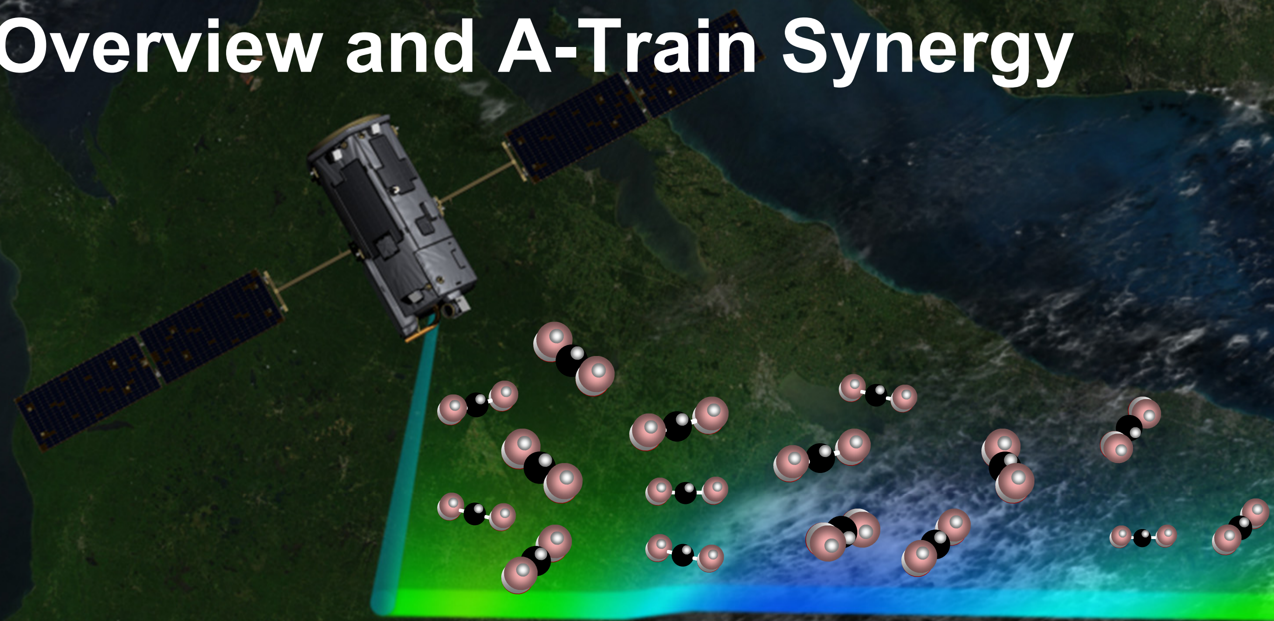
A-Train Mission Operations Working Group

Orbiting Carbon Observatory-2 (OCO-2): Science Overview and A-Train Synergy



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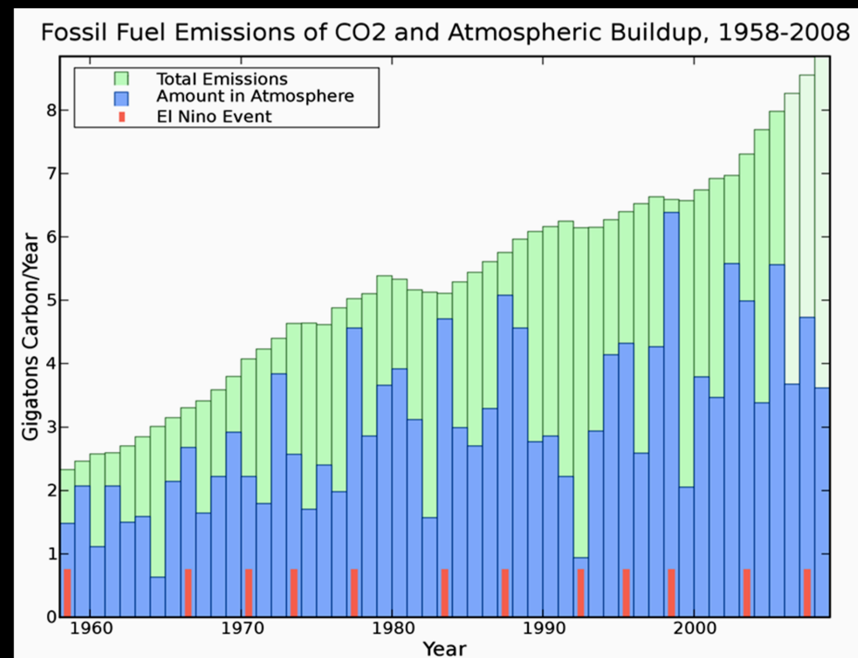
Carbon Dioxide and the Global Carbon Cycle Science

- Human activities emit >30 Gt of CO_2 into the atmosphere each year
- Less than half of this CO_2 remains in the atmosphere.
- The rest is absorbed by natural "sinks" at the Earth's surface
- Fundamental questions:
  - What processes are responsible for absorbing this CO_2?
  - Why does the sink strength vary dramatically from year to year?
  - Will the nature, location and strength of these CO_2 sinks change in the future?



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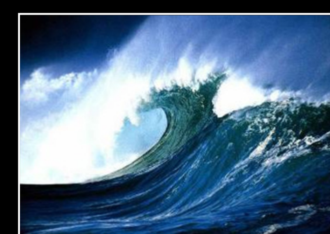
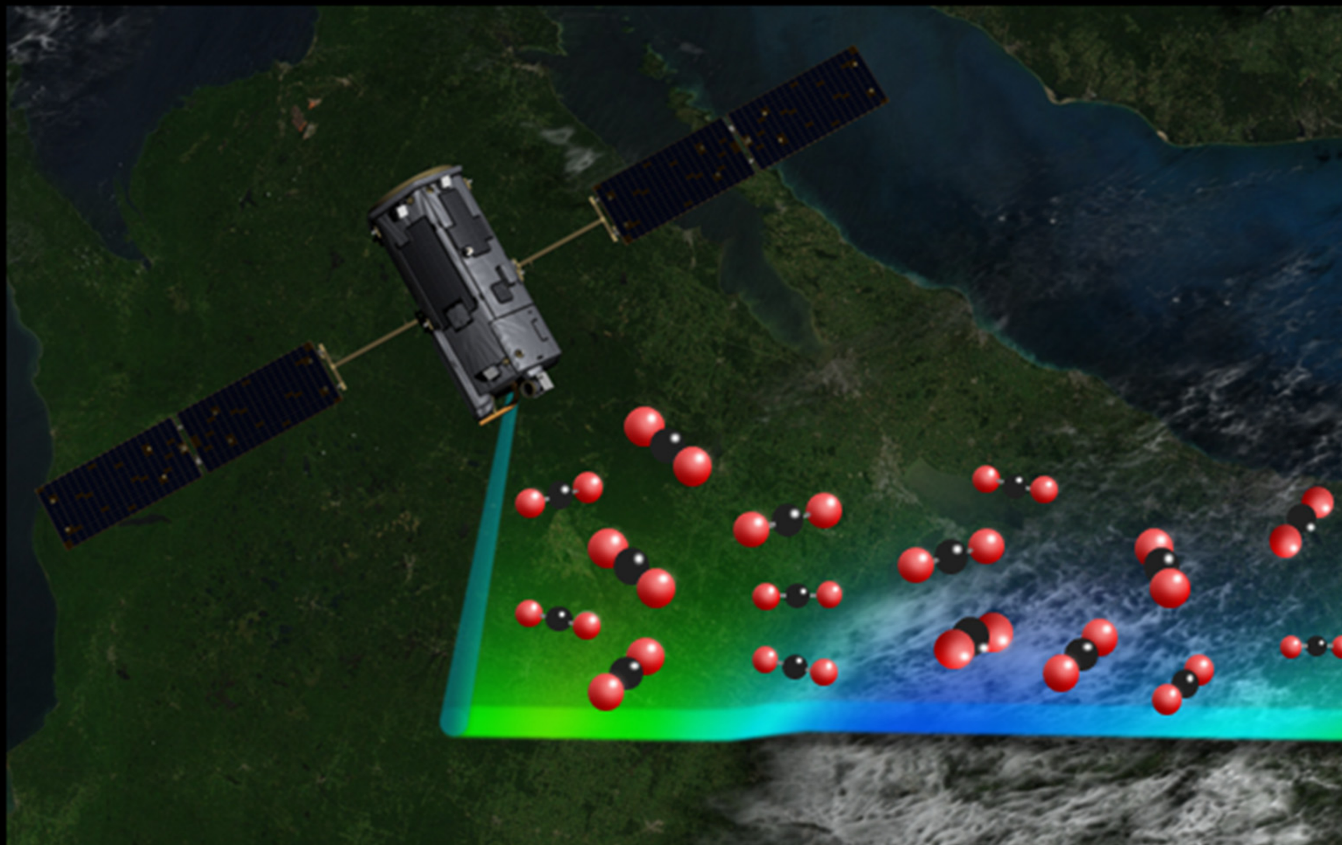


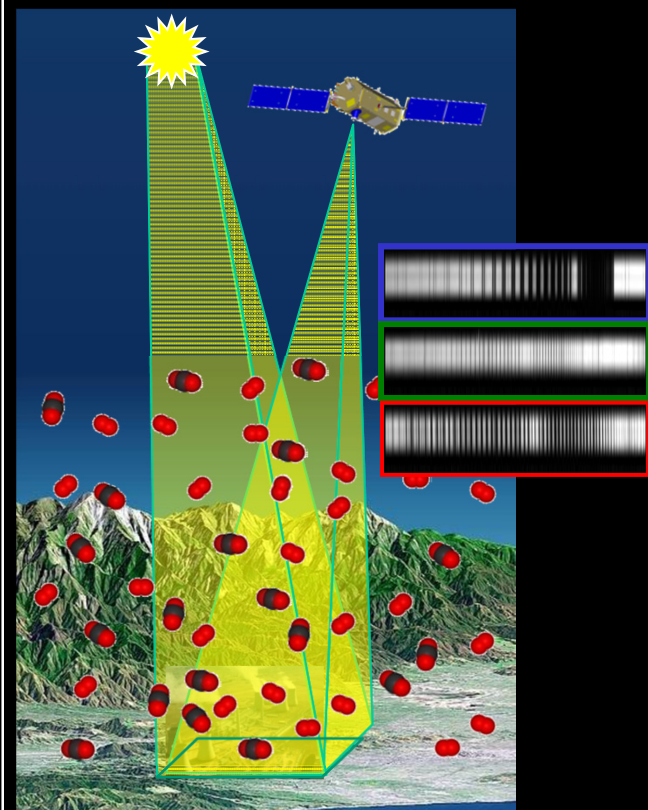
The NASA Orbiting Carbon Observatory (OCO)



NASA's Orbiting Carbon Observatory (OCO) was designed to provide global estimates of atmospheric carbon dioxide (CO_2) with the sensitivity, accuracy and sampling density needed to quantify regional scale carbon sources and sinks and characterize their behavior over the annual cycle.

Measuring CO_2 from Space

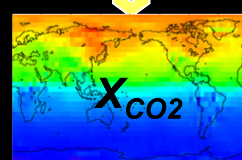
- **Record** spectra of CO_2 and O_2 absorption in reflected sunlight



- **Retrieve** variations in the *column averaged CO_2 dry air mole fraction, X_{CO2}* over the sunlit hemisphere

Initial Surf/Atm State → Generate Synthetic Spectrum → Instrument Model → Difference Spectra → Inverse Model → New State (inc. X_{CO2}) → Generate Synthetic Spectrum

Inverse Model → X_{CO2}



- **Validate** measurements to ensure X_{CO2} accuracy of 1 - 2 ppm (0.3 - 0.5%)

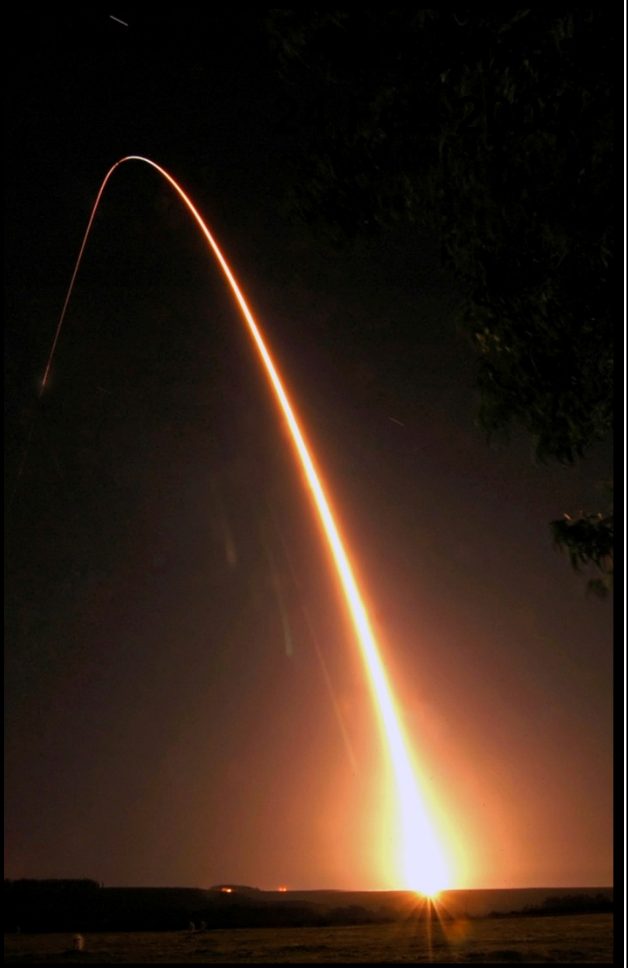
The Loss of OCO and the Birth of OCO-2

- February 2009: The OCO spacecraft was lost when its launch vehicle failed to reach orbit

- NASA commissioned a Mishap Investigation Board to determine the root cause of the anomaly and recommend corrective actions
  - Fairing failed to deploy
  - No root cause was identified, but 4 “Potential Intermediate Causes” were found

- NASA’s Earth Science Directorate instructed the OCO science team to document the justification and requirements for an OCO reflight.

- December 2009: The U.S. Congress added funding to the NASA FY2010 budget to restart the OCO Mission



A Changing Perspective

- A decade ago, when the OCO mission was proposed, the primary objective was to acquire global, space-based observations of CO_2 with the precision, coverage, and resolution needed to characterize regional scale natural CO_2 sinks, which are now absorbing more than half of the CO_2 that is being emitted by human activities
- More recently, the interest in global, space-based observations of greenhouse has intensified, but the focus has shifted, emphasizing the need to quantify emissions from human activities
  - The current emphasis is on monitoring treaty compliance and the efficacy of greenhouse gas mitigation strategies
- This change in focus, combined with new insight into the carbon cycle has introduced new challenges for remote sensing observations of greenhouse gases
- While OCO-2 is not optimized for that mission, it will provide opportunities to validate observation strategies for future CO2 monitoring missions

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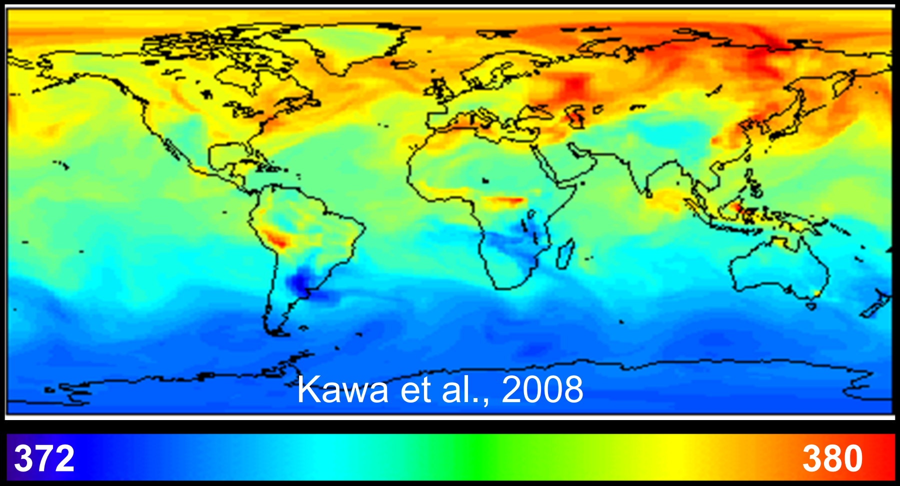
Global Measurements are Essential

- To limit the rate of atmospheric carbon dioxide buildup, we must
  - Control emissions associated with human activities
  - Understand & exploit natural processes that absorb carbon dioxide

We cannot manage what we cannot measure

- Identifying sources and sinks of atmospheric carbon dioxide from atmospheric measurements is intrinsically challenging

Plumes from medium-sized power plants (4 MtC/yr) elevate X_{CO2} levels by ~0.5% (2ppm) for 10's of km downwind [Yang and Fung, 2010].



Variations of CO_2 are rarely larger than 1-2% on 100 – 1000 km scales

The Minimum Measurable Flux

- For a satellite designed to measure the column averaged dry air mole fraction, X_{CO2}, the minimum measurable flux can be approximated as follows:
  - Assume that the minimum detectable change in X_{CO2} is $\boldsymbol{\Delta XCO2_{min}}$ (e.g. 1 ppm, or $\boldsymbol{\Delta XCO2_{min}/X_{CO2} = 0.25\%}$)
  - If the CO_2 flux, ***F***, is constant over an accumulation time interval, ***t***, the change in X_{CO2} is given by: $\boldsymbol{\Delta XCO2 = F \cdot t}$
  - If we have an average horizontal wind speed, $\boldsymbol{u(\theta)}$, in direction, $\boldsymbol{\theta}$, over time, ***t***, and a footprint has a horizontal projection, $\boldsymbol{x(\theta)}$, in direction, $\boldsymbol{\theta}$, then the residence time, $\boldsymbol{t = x(\theta) / u(\theta)}$
  - The minimum increase in the vertical column is therefore related to the minimum detectable flux as follows

    $$\Delta XCO2_{min} = F_{min} \cdot x(\theta) / u(\theta)$$

    Rearranging, gives

    $$F_{min} = u(\theta) \times \Delta XCO2_{min} / x(\theta)$$

The minimum measurable flux is proportional to the wind speed and the X_{CO2} sensitivity, and inversely proportional to the footprint size

Is 1 ppm Good Enough?

Large metropolitan areas with strong, discrete sources are easier to detect, but also rarely produce full column X_{CO2} perturbations larger than 1 ppm

TABLE B.3 Expected CO_2 Signals for Selected Metropolitan Areas

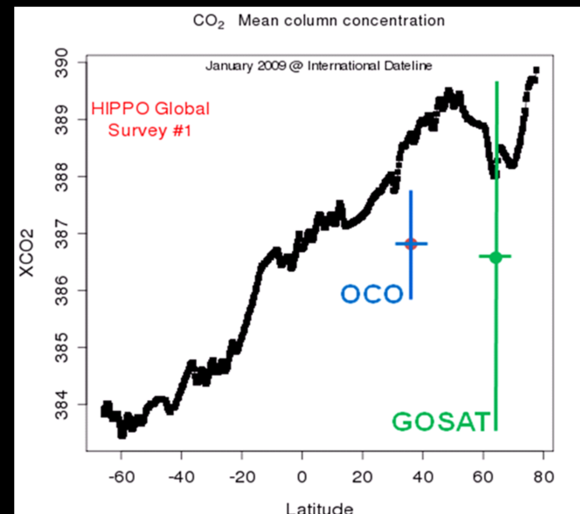
City	Area (km^2)[a]	Emissions (Mton CO_2 yr^{-1})	Emissions ($\mu mol\ m^{-2}\ s^{-1}$)	Total Column (ppm)	PBL (1 km) (ppm)
Los Angeles	3,700	73.2	14.2	0.49	4.3
Chicago	2,800	79.1	20.3	0.60	5.4
Houston	3,300	101.8	22.2	0.72	6.4
Indianapolis	900	20.1	16.1	0.27	2.4
Tokyo	1,700	64	27	0.63	5.6
Seoul	600	43	52	0.71	6.3
Beijing	800	74	67	1.1	9.4
Shanghai	700	112	116	1.8	15

(1) Committee on Methods for Estimating Greenhouse Gas Emissions Board on Atmospheric Sciences and Climate Division on Earth and Life Studies, National Research Council of the National Academy of Science, National Academies Press, 2010.

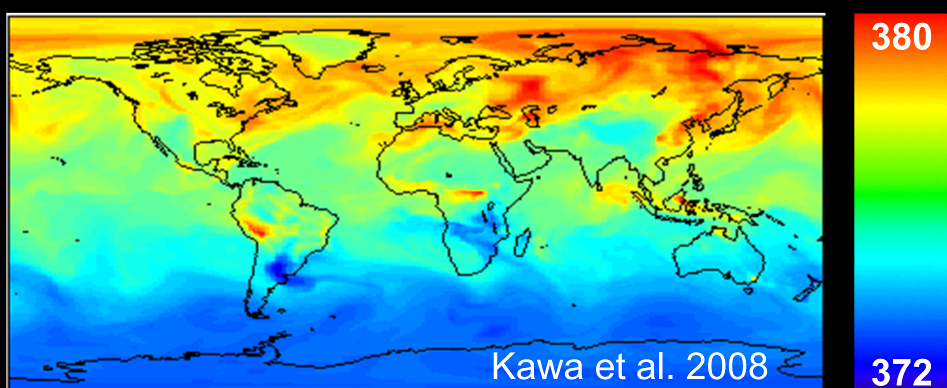
A satellite instrument with a 1 ppm sensitivity over a ~100 km down-track segment of its orbit might not detect Los Angeles, Chicago, Houston, or Tokyo.

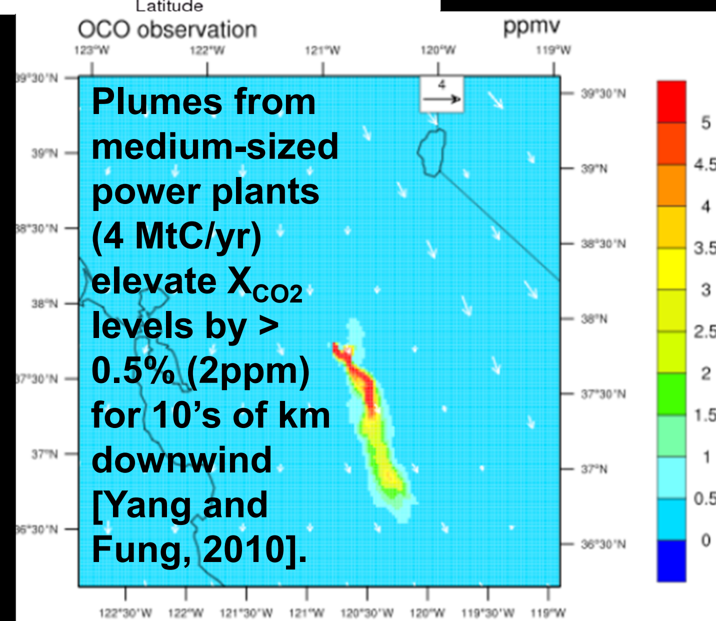
OCO-2 Is Optimized for High Precision

- CO_2 sources and sinks must be inferred from small (<2%) spatial variations in the (387 ±5 ppm) background CO_2 distribution
  - Space based NIR measurements constrain the column averaged CO_2
  - Largest variations near the surface
- High precision is essential to resolve small spatial variations in X_{CO2}
  - OCO-2 yields single-sounding random errors < 1 ppm over most of the sunlit hemisphere



Small spatial gradients in X_{CO2} verified by HIPPO flights [Wofsy et al. 2010]





OCO-2 Optimized for High Spatial Resolution

OCO-2 collects up to up to 8 soundings @ 3 Hz along a narrow swath (<10.6 km at nadir)

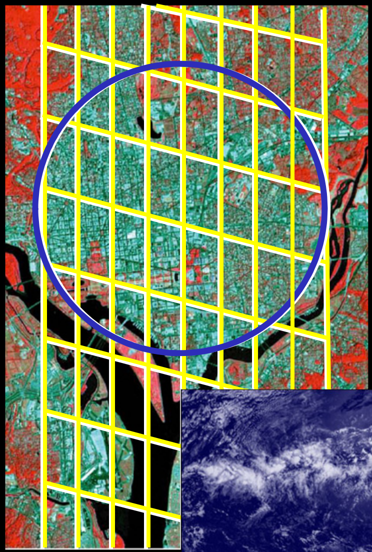
- Small footprints

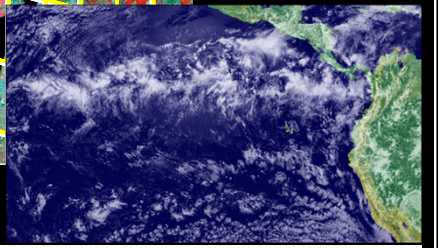
High sampling rate yields large numbers of soundings that can be averaged to increase precision

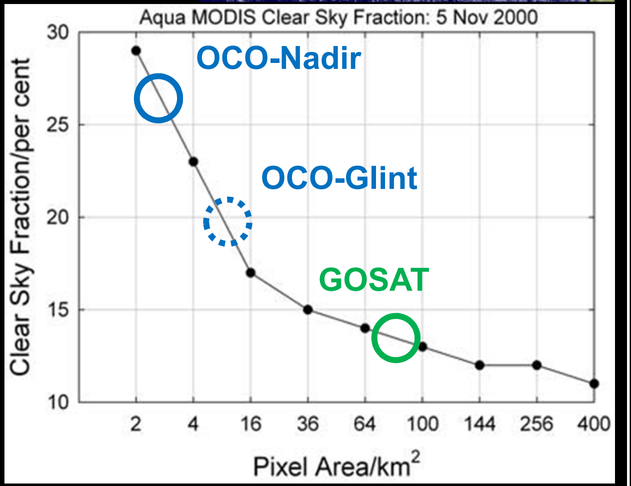
- 200 – 400 soundings per degree of latitude over sunlit hemisphere

Small footprint (<3 km^2 at nadir) increases:

- Sensitivity to discrete CO_2 point sources
  - Minimum measureable CO_2 flux inversely proportional to footprint size
- Probability of recording cloud free soundings in partially cloudy regions
  - OCO: 27% @ Nadir, 19% for Glint
  - GOSAT (85 km^2): ~10%







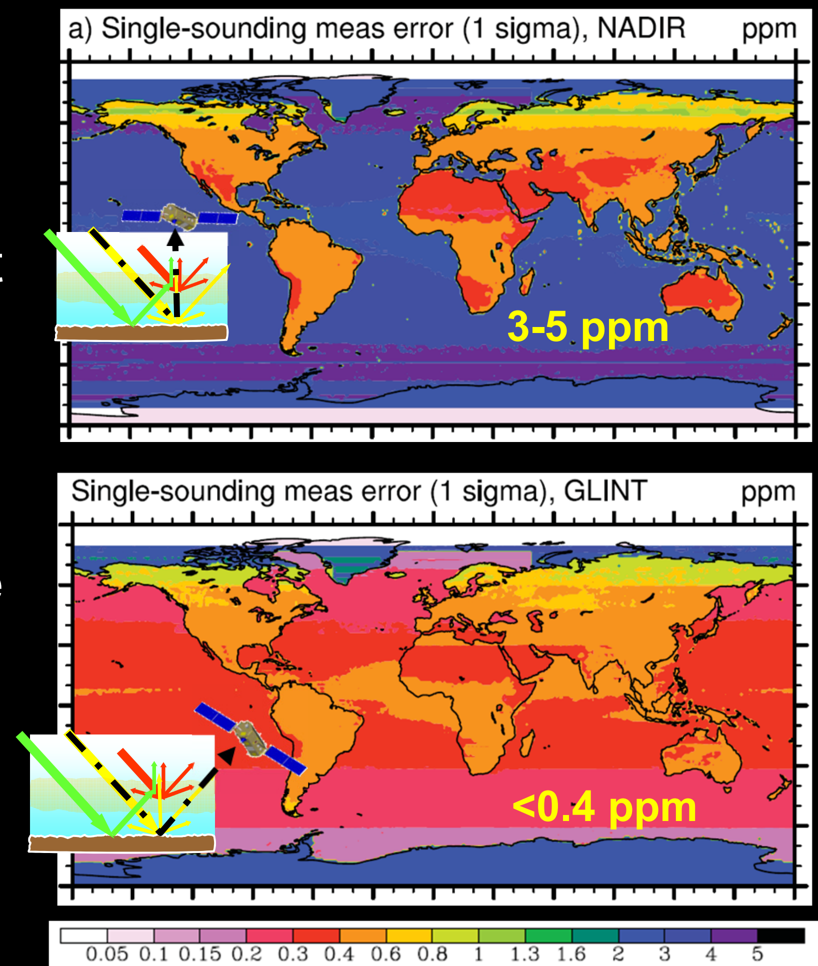
OCO-2 Provides High SNR over both Continents and Oceans

Full global coverage is needed to:

- Resolve X_{CO2} over land and ocean for the full range of latitudes, minimizing errors from CO_2 transport in and out of the observed domain

Near IR solar remote sensing measurements of CO_2 over the ocean are especially challenging because the ocean reflects little sunlight

- Typical nadir reflectances are between 0.5 and 1%
- Most of the sunlight reflected by the ocean surface is scattered into a narrow range of angles, producing the familiar “glint” spot

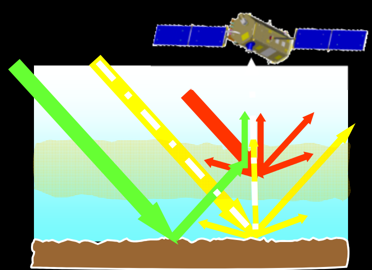


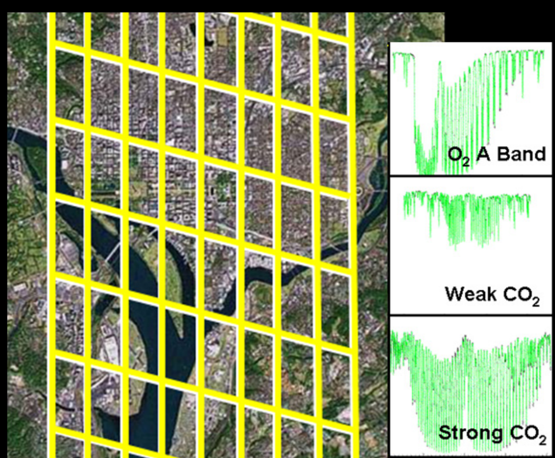
OCO single sounding random errors for nadir and glint [Baker et al. ACPD, 2008].

Same Three Observation Modes

Nadir Observations:

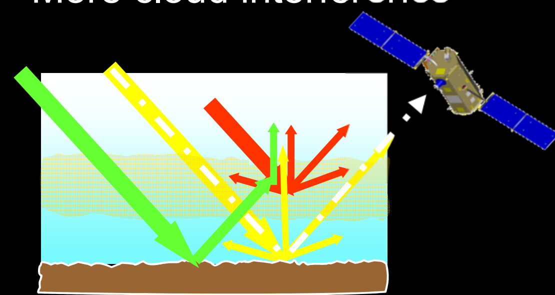
+ Small footprint (< 3 km^2)
– Low Signal/Noise over dark surfaces (ocean, ice)

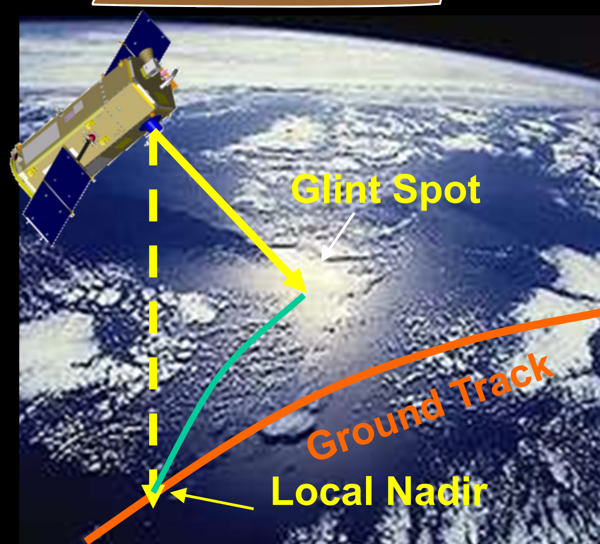




Glint Observations:

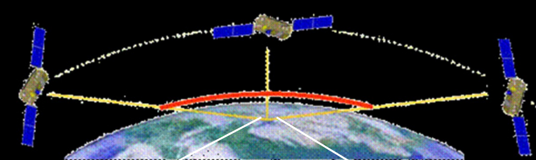
+ Improves Signal/Noise over oceans
– More cloud interference

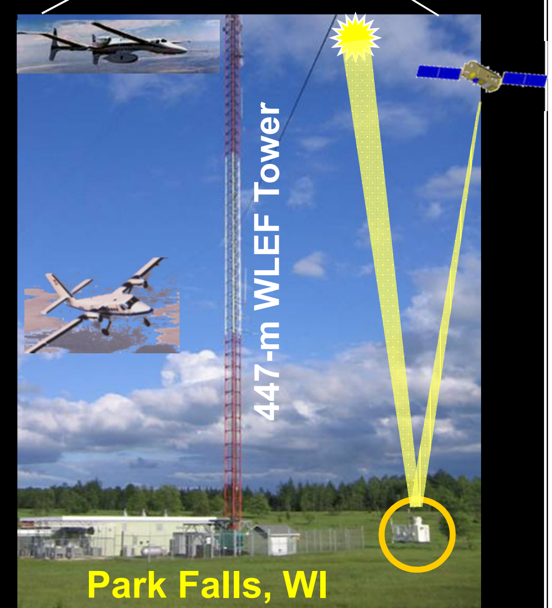




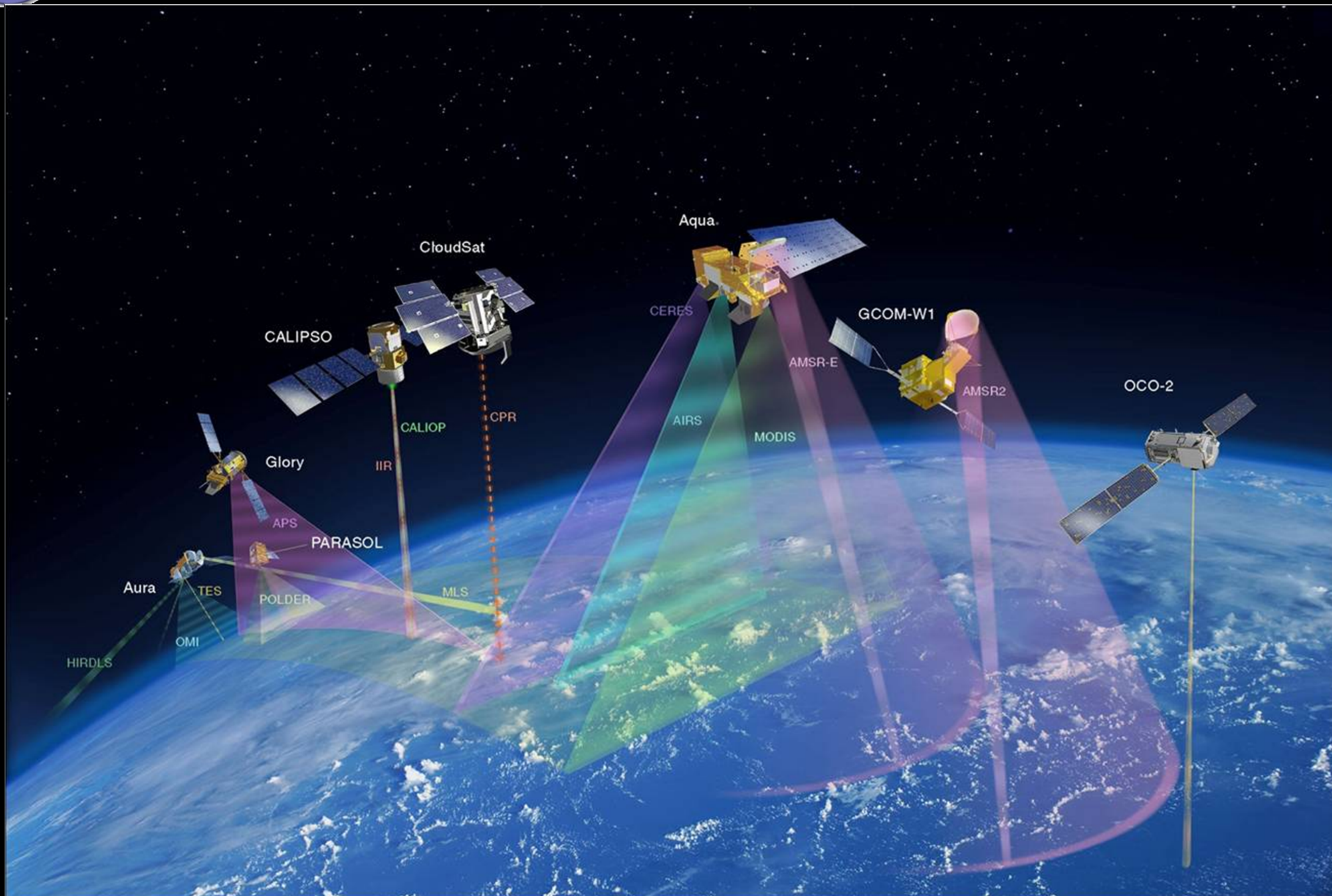
Target Observations:

- Validation over ground based FTS sites, field campaigns, other targets





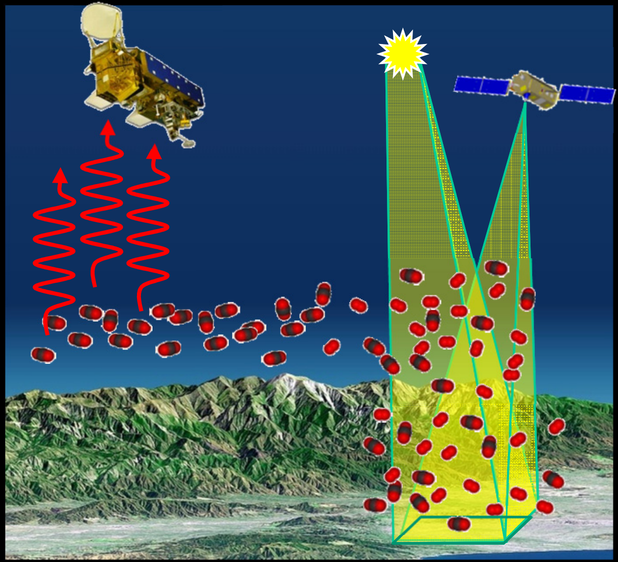
Still Flying at the Head of the A-Train

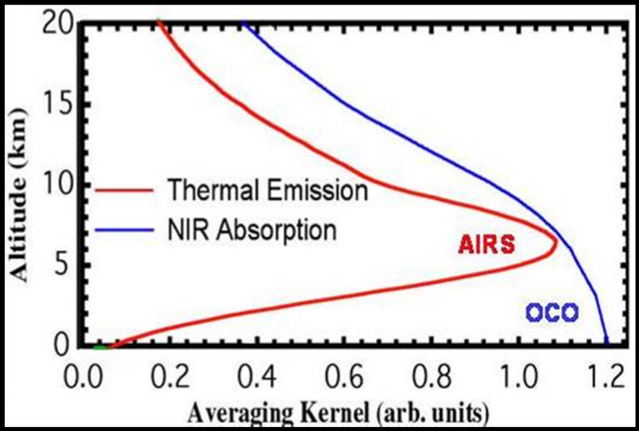


Measuring CO_2: Synergy with AIRS and TES

Atmospheric CO_2 can be inferred from both thermal IR or solar remote sensing data

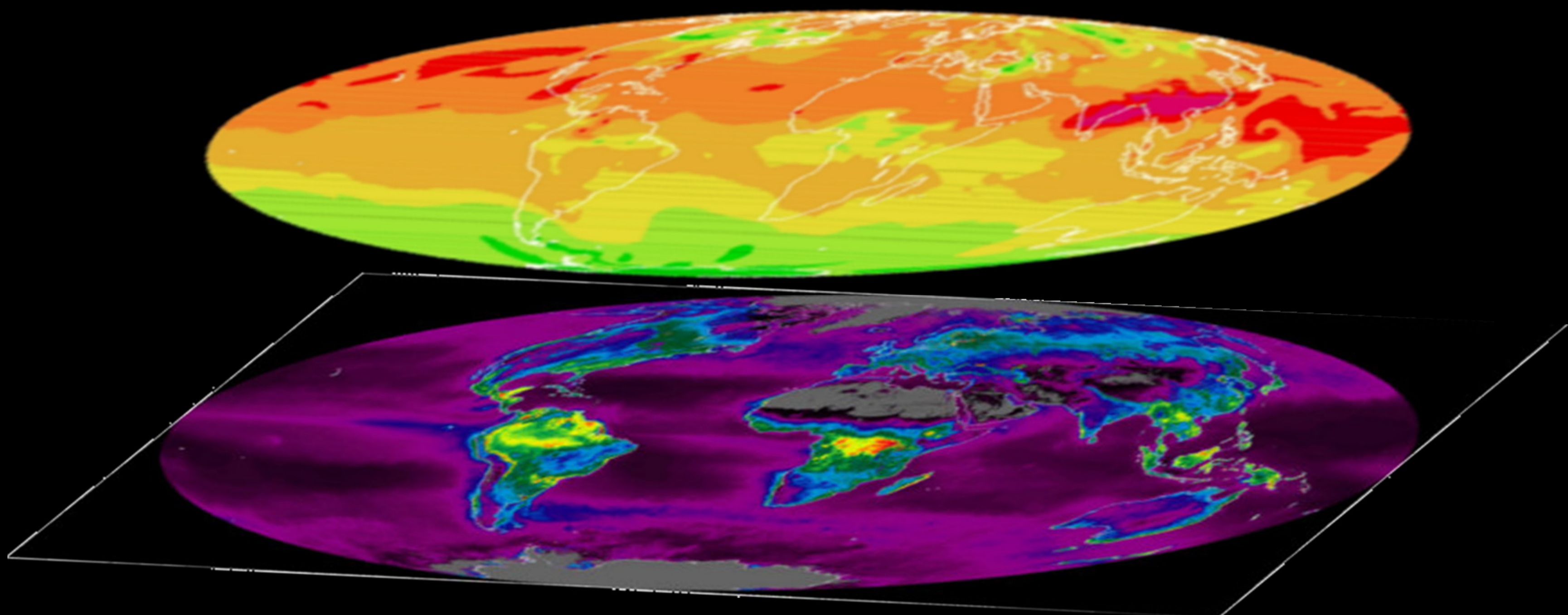
- Thermal IR instruments (AIRS,TES , IASI) measure CO_2 above the mid-troposphere
  - Directly measure the greenhouse forcing by CO_2 in the present climate
  - Provides limited information on sources/sinks
- Solar NIR instruments (GOSAT, OCO-2) measure the total CO_2 column
  - Most sensitive to surface fluxes
  - Provides insight needed to predict future rates of CO_2 buildup and climate impacts
- Combining solar NIR and thermal IR measurements could provide insight into vertical atmospheric transport of CO_2





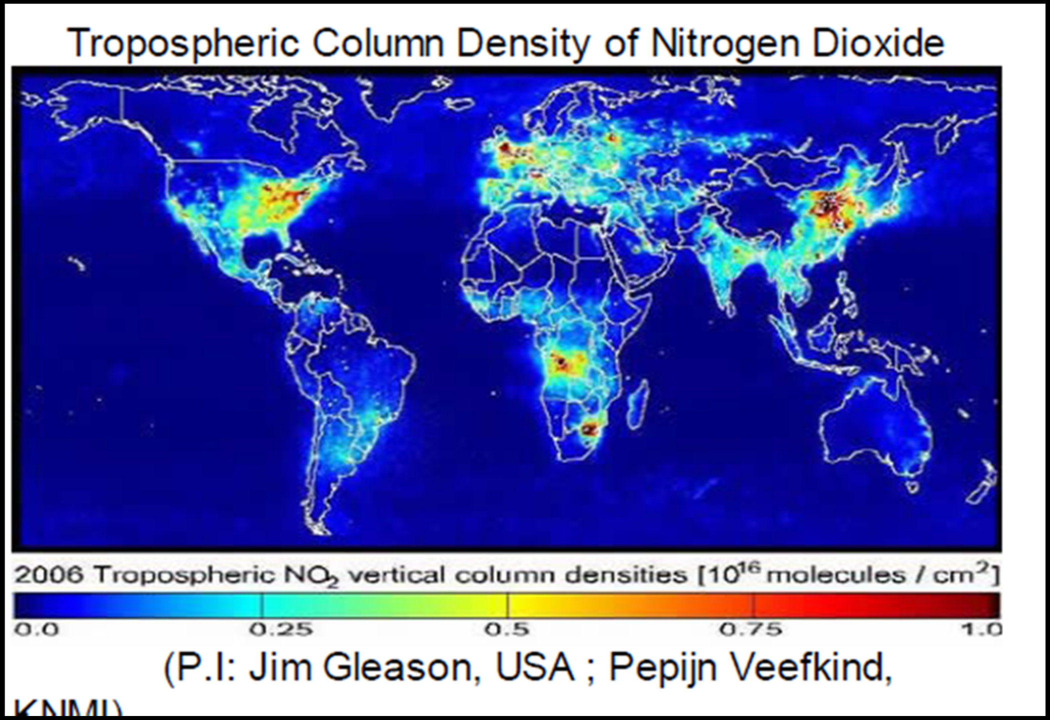
OCO-2 Synergies with MODIS Carbon cycle Measurements

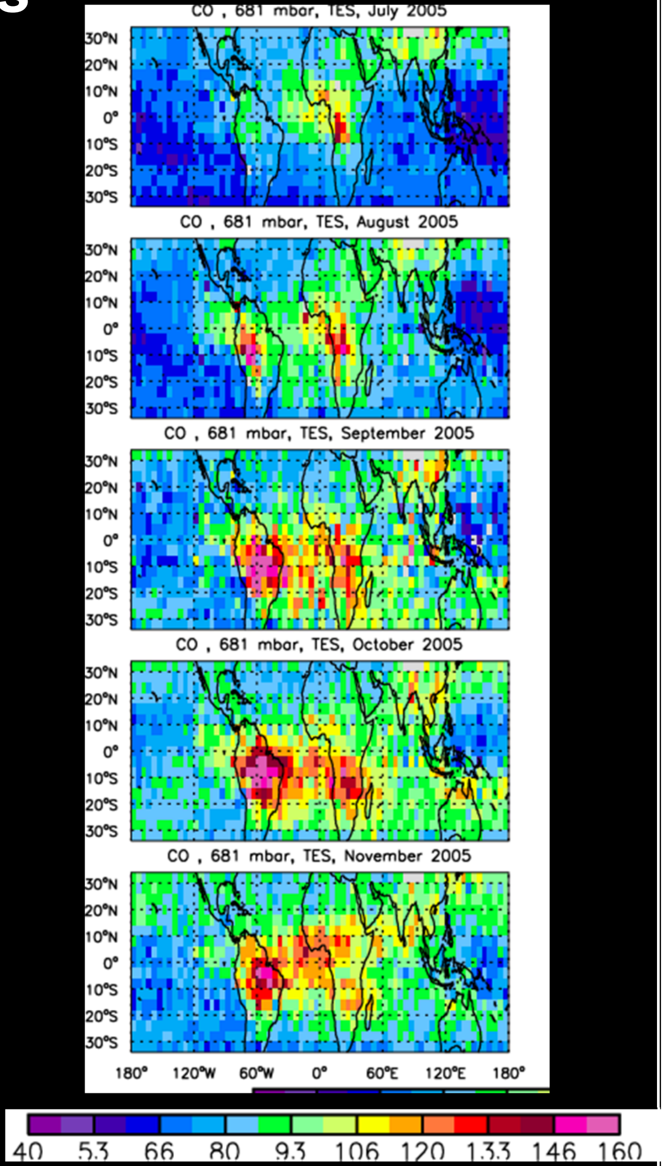
- OCO-2 X_{CO2} estimates could be combined with coincident MODIS measurements of land cover type, leaf area index, net primary production, fire occurrence, and ocean color to help quantify the CO_2 fluxes associated with these processes.



Other Trace Gases

- Combining OCO-2 X_{CO2} with AIRS and TES CO observations and OMI NO_2 could help to discriminate biomass burning events from other CO_2 emissions





OCO-2 Synergies with A-Train Cloud and Aerosol Measurements

Characterization of optically thin clouds and aerosols

- OCO-2 cloud and aerosol measurements could be combined with CloudSat and CALIPSO measurements to more completely constrain the occurrence of thin, high clouds and their impact on the solar radiation budget.
  – A-Band spectrometers were originally included on both CloudSat and CALIPSO, but were descoped during the implementation phases of these missions to control cost
  – The OCO-2 A-Band observations will help to address this need

- High-resolution O_2 A-band measurements can be combined with MODIS cloud measurements to
    - Improve detection over continents and ice-covered surfaces
    - Provide information about the vertical distribution of particles
  – Spectral signature of water ice absorption in 1.61 and 2.06 µm bands clearly discriminates ice and liquid water droplets

Contributions of other A-Train Data Products to OCO-2 Retrieval Accuracy

- Uncertainties in clouds and aerosols contribute an important source of error in OCO retrievals of X_{CO2}
  - Clouds that occupy a small fraction of an OCO-2 footprint (<5%) pose especially challenging problems
  - Cloud shadow also contribute optical pathlength uncertainties
  - High resolution MODIS cloud products would help validate OCO cloud screening algorithm at sub-footprint scales
  - Cloud and aerosol optical properties and vertical distribution measurements from CloudSat , CALIPSO, and Glory could be used to initialize and help validate the cloud and aerosol retrievals by OCO-2.
- AIRS temperature and humidity measurements could be used to initialize and/or validate OCO water vapor and temperature retrievals.
- Polarimetric measurements from Glory may provide improved estimates of the degree of polarization of the reflected solar radiation field and its impact of X_{CO2} retrievals.

Summary

- OCO-2 will fly at the front of the A-train, sharing a ground track with Aqua
- The OCO-2 Instrument will collect over 500,000 to 1,000,000 soundings/day along a narrow swath, either along the ground track, or in the direction of the local "glint" spot, where sunlight is specularly reflected from the surface
- OCO-2 X_{CO2} measurements could be combined with
  - TES and AIRS CO_2 observations to provide additional constraints on the vertical profile of CO_2.
  - MODIS land products to yield additional information about net primary production
  - TES and AIRS observations of CO, and OMI observations of NO_2 to discriminate between combustion events and other CO2 emissions
- OCO-2 is currently on track for a February 2013 Launch